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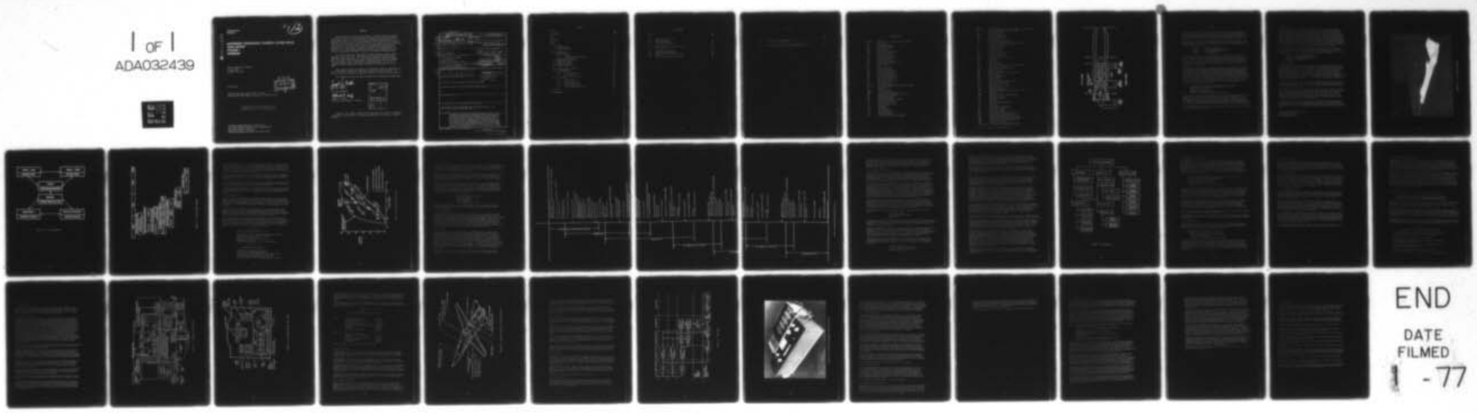

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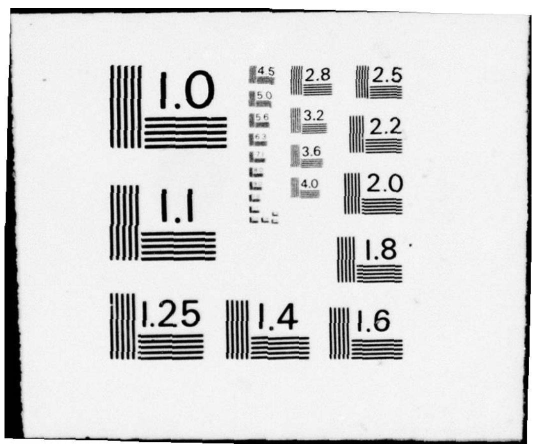
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AFAPL-TR-76-61
VOLUME I

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INTEGRATED PROPULSION CONTROL SYSTEM (IPCS) FINAL REPORT VOLUME I SUMMARY

BOEING AEROSPACE COMPANY
P.O. BOX 3999
SEATTLE, WA. 98124

AUGUST 1976

TECHNICAL REPORT AFAPL-TR-76-61 VOLUME I
FINAL REPORT FOR PERIOD 1 MARCH 1973 - 30 AUGUST 1976

AIR FORCE AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This final report was submitted by Boeing Aerospace Company, under contract F33615-73-C-2035. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project Number 3066, Task Number 03 and Work Unit Number 42 with Joseph J. Batka, AFAPL/TBC as Project Engineer. Mr. G. W. N. Lampard of Boeing Aerospace Company was technically responsible for the work.

This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Joseph J. Batka

JOSEPH J. BATKA
Project Engineer

FOR THE COMMANDER

Charles E. Bentz

CHARLES E. BENTZ
Technical Area Manager - Controls

ACCESSION for

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20. ABSTRACT

The Integrated Propulsion Control System (IPCS) program was conducted to pursue and demonstrate the advantages of integrated propulsion controls. The program encompassed the design, build, flight qualification, and flight testing of control modes, software, and hardware. The flight test vehicle was an F-111E. The left inlet and TF30-P-9 engine were modified to operate under control of an HDC-601 computer. Two sets of hardware were built or modified and two sets of software were developed; one implemented the bill-of-materials control laws and one implemented control laws developed under contract. A step-by-step sequence of tests of increasing complexity demonstrated suitability for flight. Fifteen flights were conducted to evaluate the IPCS. The program description and results are summarized in this document.

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CONTENTS

ILLUSTRATIONS

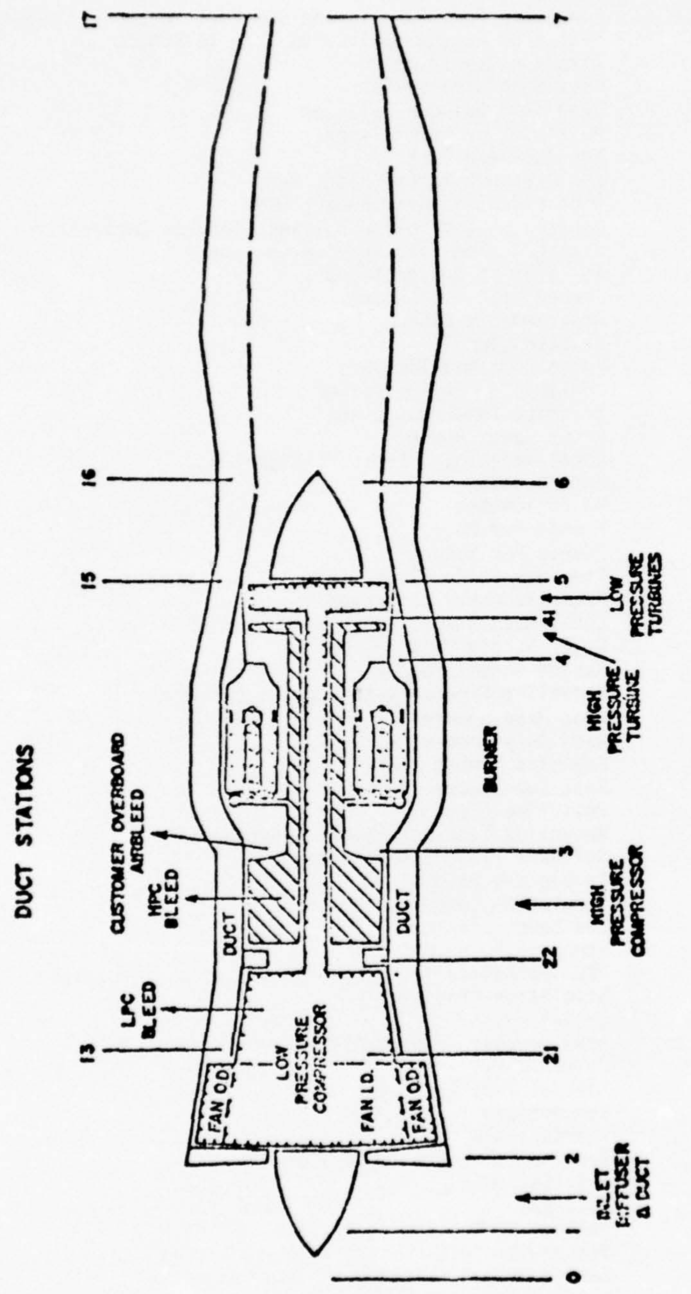
TABLES

IPCS NOMENCLATURE

A/B	Afterburner
ABC1-ABC8	Afterburner Control Scheduled Functions in BOMDIG
Aj	Nozzle Area
A/D	Analog-to-Digital
ATP	Acceptance Test Procedure
BITE	Built In Test Equipment
BLFT	Baseline Flight Test
BOM	Bill-of-Materials
BOMDIG	Bill-of-Material Digital Control
CADC	Central Air Data Computer
CCU	Computer Control Unit
CDR	Critical Design Review
CFE	Contractor Furnished Equipment
CLBT	Closed-Loop Bench Test
CMU	Computer Monitor Unit
CPC	Computer Program Component
CPCEI	Computer Program Contract End Item
CPU	Central Processor Unit
D/A	Digital-to-Analog
dB	Decibel
DCS	Digital Computer System
DCU	Digital Computer Unit
DEM	Diffuser Exit Mach Number
DFRC	Dryden Flight Research Center
DIB	Discrete Input Buffers
DIO	Direct Input/Output Channel
DMA	Direct Memory Access Channel
DOB	Discrete Output Buffers
DPCU	Digital Propulsion Control Unit
DS	Design Specifications
ECS	Environmental Control System
EIB	Engine Interface Box
ENC	Exhaust Nozzle Control
ENC1-ENC8	Exhaust Nozzle Scheduled Control Functions in BOMDIG
EPR	Engine Pressure Ratio
EX	Excitation
FAT	Flight Assurance Test
FBCANG	Feedback Cam Angle
FMEA	Failure Mode & Effect Analysis
FMECA	Failure Mode, Effect, and Criticality Analysis
GFE	Government Furnished Equipment
GSE	Ground Support Equipment
HPC	High Pressure Compressor
HSPT	High Speed Paper Tape Punch & Reader
HMC	Hydromechanical Control
Hz	Hertz (= cycles per second)
I.C.	Initial Condition
ICD	Interface Control Document
IFU	Interface unit
I/O	Input/Output
KD	Distortion Index
LLMUX	Low Level Multiplexer
LM	Local Mach Number
LPC	Low Pressure Compressor
LRD	Lamp and Relay Drivers
LVDT	Linear Variable Differential Transformer

MFC	Main Fuel Control
MFC1-MFC7	Scheduled Functions in the BOM fuel Control, Represented by Tables or Polynominal Curve Fits in BOMDIG
MN	Airplane Mach Number
MSB	Most Significant Bit
MTBF	Mean Time Between Failures
MUX	Multiplex or Multiplexer
NSP	Non Standard Part
N1	Low Pressure Rotor Speed, PRM
N2	High Pressure Rotor Speed, RPM
OCV	Oscillator Controlled Voltage Circuits Demodulators
P	Pressure, See Illustration next page for Station Designations
Pb	Burner static pressure
PC	Programmable Clock
P/C	Printed Circuit
PCM	Pulse Code Modulation
PDR	Preliminary Design Review
PIL	Priority Interrupt Lines
PLA	Power Lever Angle
PLM	Local-Mach Total Pressure Signal
P/N	Part Number
POT	Potentiometer
PPH	Pounds Per Hour
PPS	Pounds Per Second
PRBC	Pressure Ratio Bleed Control (12th Stage Bleed)
PRI	Power Recovery Interrupt
PSLM	Local-Mach Static Pressure Signal
PSU	Power Supply Unit
RAM	Random Access Memory
RFD	Recycling Frequency-to-Digital Converters
RMS	Root Mean Square
ROM	Read Only Memory
RNI	Reynolds Number Index
RSS	Root Sum Square
RTC	Real Time Clock
RTD	Recycling Time-to-Digital Converters
SFCO	Software Field Change Order
S&H	Sample and Hold
SIA	Simulation Interface Adapter
SLS	Sea Level Static
SMD	Stepping Motor Drivers
SMITE	P&WA Technique for Iterative Solutions in Digital Simulation Program
S/N	Serial No.
SOAPP	P&WA Modular Program Assembly Procedure
SOD	Solenoid Drivers
STE	Special Test Equipment
T	Temperature
T/C	Thermocouple
TIGT	Turbine Inlet Gas Temperature
TSU	Test Set Unit
TTY	Teletype
VCO	Voltage Controlled Oscillator
Vex	Sensor Excitation Voltage
Vo	Sensor Output Voltage
Wa	Airflow Rate, lb/hour
WAR2	Corrected Air Flow Rate at Station 2
Wf	Fuel Flow Rate, Gas Generator, lb./hr.
WFG	Commanded Fuel Flow Rate, Gas Generator
WFZi	Commanded Afterburner Fuel Flow, ith Zone, i=1,..., 5
XAJP	Resolver Angle on Nozzle Position Feedback
XAJV	Nozzle Control Pilot Valve Position
XCON	Cone Actuator Position
XOO	Afterburner Control Power Piston Position
XSPK (XORLS)	Spike Position (normalized spike position)

A suffix "S" indicates a sensed variable .



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ENGINE STATIONS
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INLET DIFFUSER & DUCT
FAN O.D.
FAN I.D.
LOW PRESSURE COMPRESSOR
LPC BLEED
DUCT
HPC BLEED
CUSTOMER OVERBOARD AIRBLEED
HIGH PRESSURE COMPRESSOR
BURNER
HIGH PRESSURE TURBINE
LOW PRESSURE TURBINES

Summary

The operational capability of aircraft can be expanded by use of integrated propulsion controls. Steady-state and transient performance can be improved, engine life can be extended, and crew work load can be reduced. While these improvements are applicable to both military and civilian aircraft, implementation has been impeded by the limitations of hydromechanical controls and the increasing complexity of newer propulsion systems.

The Air Force sponsored the Integrated Propulsion Control System (IPCS) program to pursue and demonstrate the advantages of integrated propulsion controls. The description of the program and significant results are set forth in the final report. The four volumes of the final report are as follows:

VOLUME I	SUMMARY AND RECOMMENDATIONS
VOLUME II	IPCS PROGRAM TECHNICAL DESCRIPTION
VOLUME III	IPCS FLIGHT TEST REPORT
VOLUME IV	IPCS METHODOLOGY

The IPCS program encompassed the design, build, flight qualification, and flight testing of propulsion control modes, software, and hardware. The flight test vehicle was an F-111E. The left inlet and TF30-P-9 engine were modified to operate under full-authority control of an HDC-601 digital computer. Government participants in the program were the Air Force Aero-Propulsion Laboratory, NASA Lewis Research Center, and NASA Dryden Flight Research Center. Major contractors were the Boeing Aerospace Company, Honeywell, Inc., and Pratt and Whitney Aircraft.

Two complete sets of propulsion and control hardware were built or modified for IPCS. Two sets of software were developed; one (BOMDIG) was a digital representation of the bill-of-material control modes; the other (IPCS) implemented advanced control modes developed under contract. A step-by-step sequence of tests of increasing complexity demonstrated suitability for flight. Component and subsystem tests were conducted followed by a bench test of the electronics interfaced with the modified fuel controllers. A real-time hybrid simulation of the engine and inlet was used to close the loop in the bench tests. The controllers were mated to TF30-P-9 engines and subjected to sea-level-static, then altitude tests. This was followed by extensive ground testing in the F-111E aircraft. Fifteen flights were conducted to evaluate the IPCS. The following operational advantages were demonstrated in the flight test program:

- Faster engine acceleration; both gas generator and afterburner
- Improved thrust and SFC at some flight conditions
- Reduced thrust at flight idle
- Extended service ceiling
- Reduced or eliminated ground trim
- Automatic stall detection and stall recovery detection

One of the IPCS program goals was the demonstration of a management methodology that could reduce the cost and risk in the development of complex systems. The essence of IPCS methodology resides in three concepts: (1) Early planning for integration, (2) Early involvement of all concerned parties, and (3) Freer interorganizational communication at all levels than is considered common in weapons system programs. The effectiveness of the IPCS methodology is demonstrated by the fact that the program was on schedule at completion.

A list of recommendations for work that would expedite the development of a future integrated propulsion control system is included.

1.0 INTRODUCTION

The operational capability of aircraft can be expanded by use of integrated propulsion controls. Steady-state engine performance (thrust, SFC) can be improved by operating closer to the engine limits. External disturbances can be tolerated by shifting the engine operating point for the duration of the disturbance. Faster, smoother transients can be accomplished by retreating from the operating limits (sacrificing fuel economy or peak thrust momentarily) during accels and decels. Engine life and time between overhauls can be extended by more consistent avoidance of momentary over-temperature and over-stress conditions and by miminizing temperature cycling. Crew work load may be reduced through a greater degree of automation. Ground trimming of the engines can be reduced or eliminated. While these improvements are applicable to both military and civilian aircraft, implementation has been impeded by the inherent limitations of hydromechanical controls and by the fact that the newer, more complex propulsion systems are more difficult to control.

The Air Force* sponsored the Integrated Propulsion Control System (IPCS) program under Contract No. F33615-73-C-2035 to pursue and demonstrate the advantages of integrated propulsion controls. The description of the program and significant results are set forth in the final report. The four volumes of the final report are as follows:

Volume I SUMMARY AND RECOMMENDATIONS
Volume II IPCS PROGRAM TECHNICAL DESCRIPTION
Volume III IPCS FLIGHT TEST REPORT
Volume IV IPCS METHODOLOGY

1.1 PROGRAM OVERVIEW

The IPCS program encompassed the design, build, flight qualification and flight testing of propulsion control modes, software, and hardware. The flight test vehicle was an F-111E airplane owned by the government. The left-hand inlet and TF30-P-9 engine were modified to operate under the full-authority control of an Honeywell HDC-601 digital computer mounted in the aircraft weapons bay. The flight test aircraft is shown in Figure 1.1-1. Key tests were conducted and specialized technical guidance was provided by NASA; the Dryden Flight Research Center (DFRC) and the Lewis Research Center (LeRC). Major contractors were Boeing Aerospace Company, Honeywell, Inc., G&AP Division, and Pratt and Whitney Division of United Technology (P&WA™). A diagram showing organizational responsibilities is given in Figure 1.1-2.

The contract date was 1 March 1973. (The program schedule is shown in Figure 1.1-3.) An analysis and design phase of about fifteen months followed; the final design review was conducted late in May 1974. Baseline tests were conducted to document the characteristics of the test engines and aircraft.

Two complete sets of hardware were fabricated or modified for the IPCS program. The first set of hardware and software was delivered by Honeywell on 28 October 1974. System level tests at the P&WA fuel system test bench facility began immediately. The electronic hardware was mated with the modified Bendix fuel controls and a modified F-111 inlet actuation module and operated, closed loop, using simulations of the engine and inlet aerodynamics to close the loop. A two-month test series followed during which various hardware and software deficiencies were corrected.

The modified fuel controls were then installed on the two TF30-P-9 engines that were dedicated to the IPCS program, engines P-676627 and P-676629. Testing commenced in the sea-level test cell on 21 January 1975 and continued through 27 March 1975. A total of 97 hours and 57 minutes running time was accumulated on the two engines during the sea level tests.

*Air Force Aero Propulsion Laboratory
Air Force Systems Command
United States Air Force
Wright-Patterson AFB, Ohio

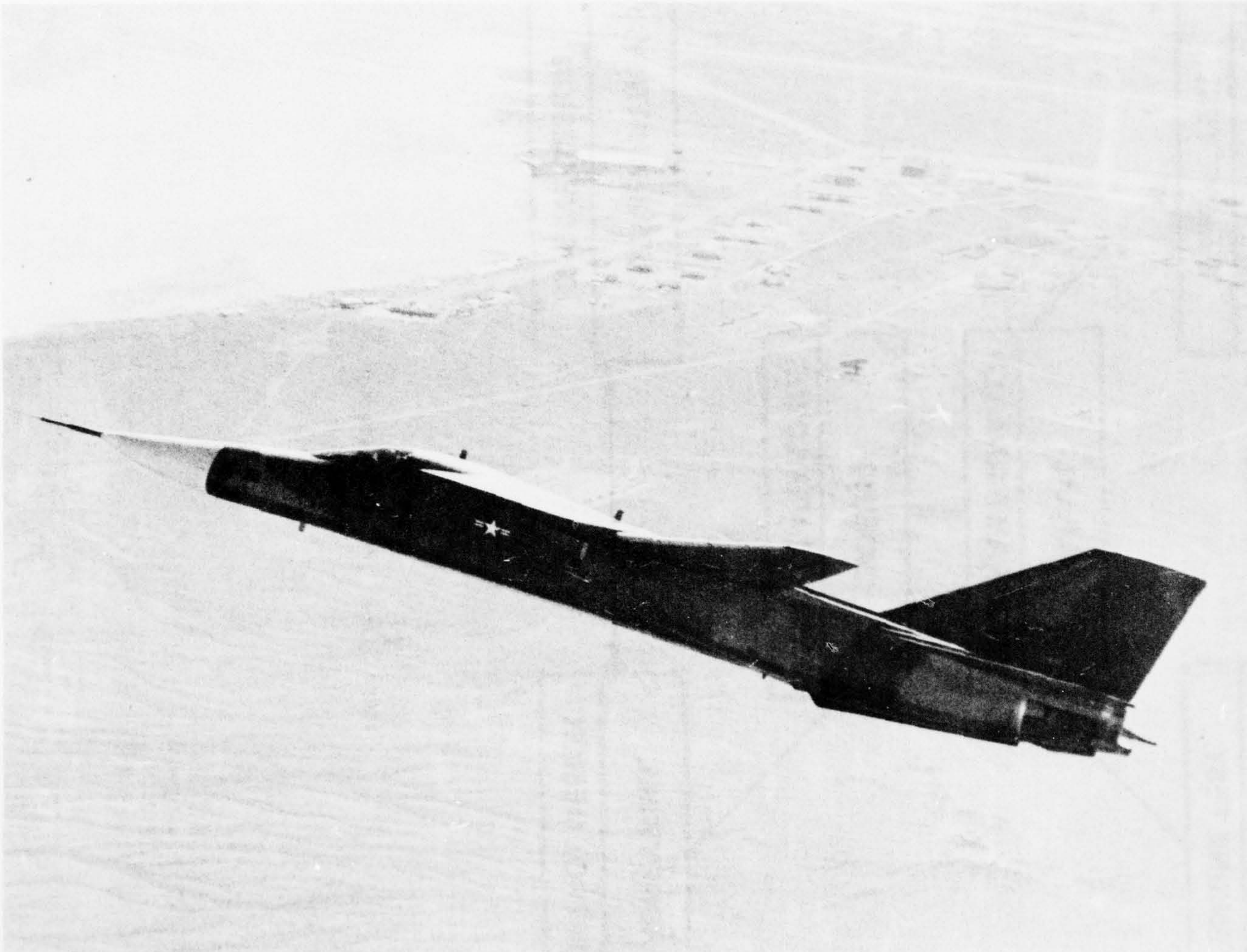


FIGURE 1.1-1 F-111 TEST AIRPLANE

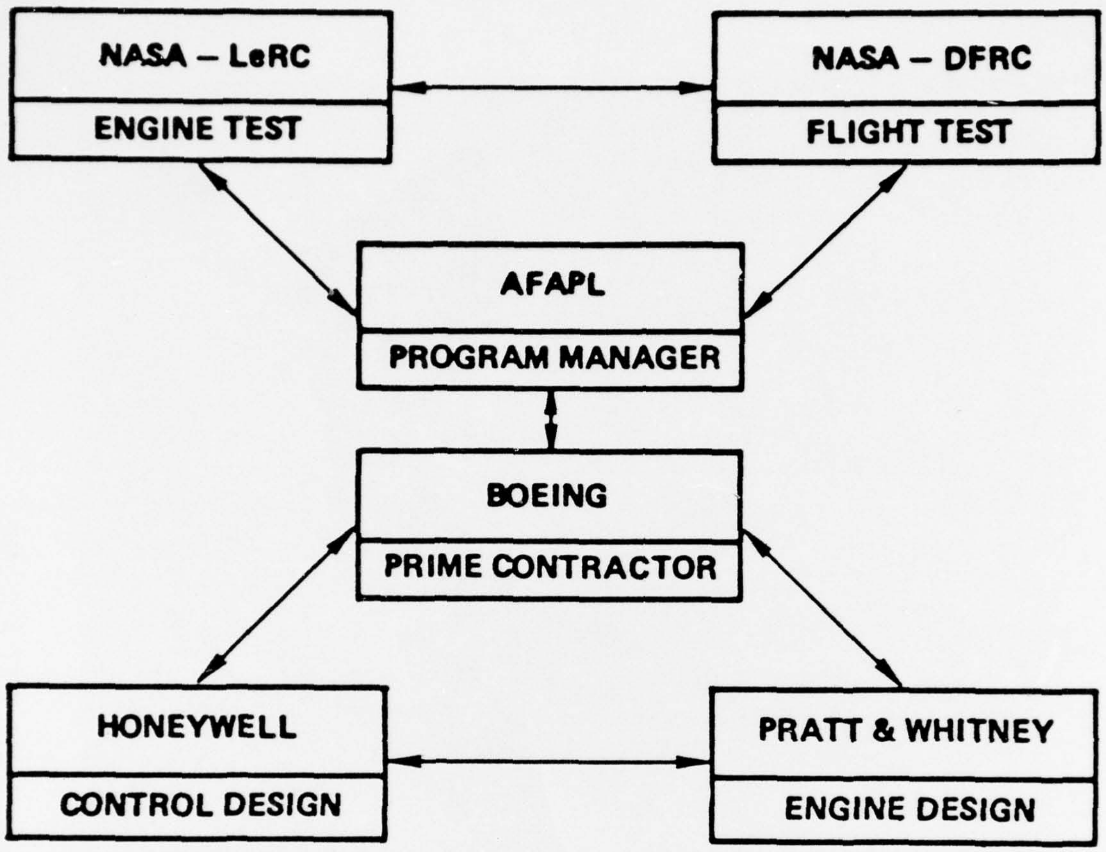


Figure 1.1-2 IPCS Organization

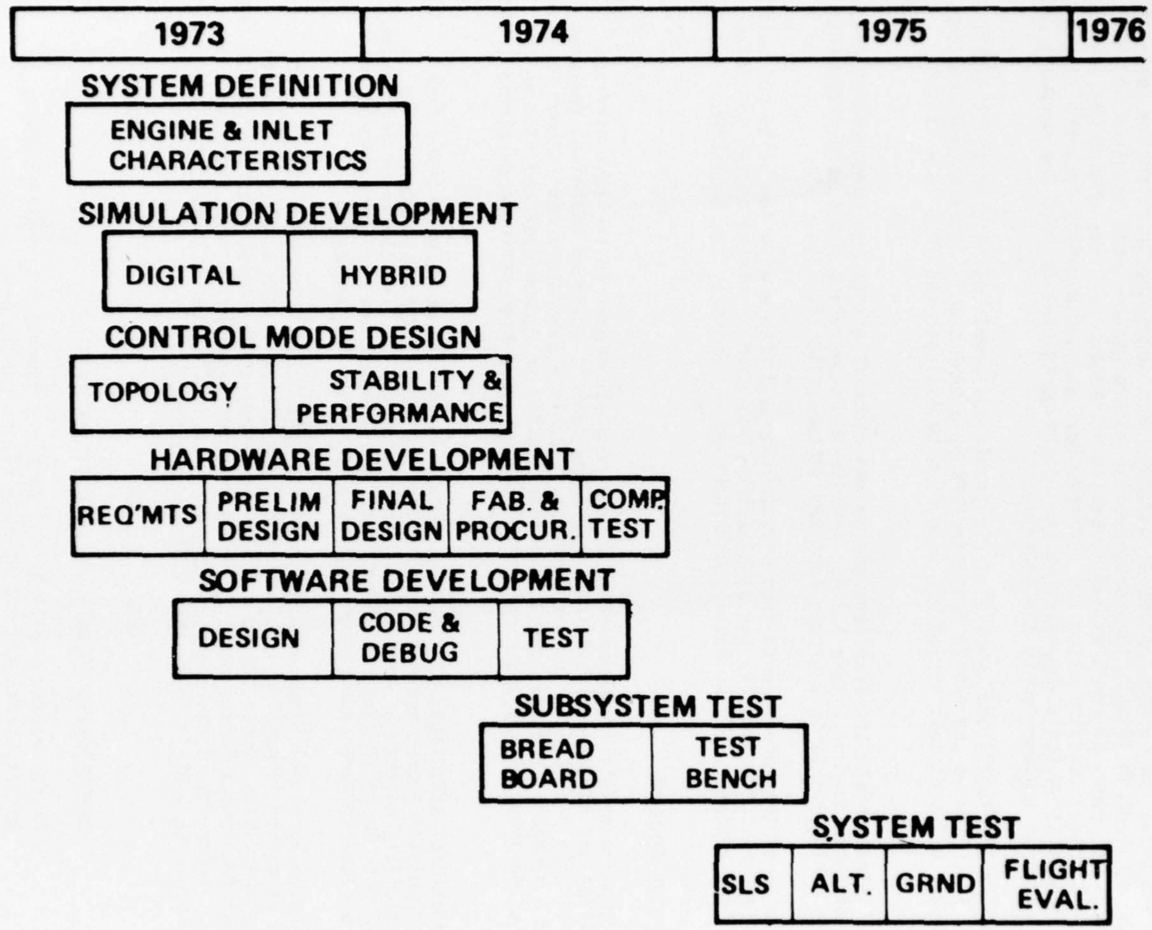


Figure 1.1-3 IPCS Program Schedule

One engine (P-676629) and set of controller hardware were subjected to extensive tests in the NASA/LeRC altitude facility. The comprehensive nature of the tests resulted in the accumulation of 243 hours of run time and 70 stalls on the engine. The engine was sent to the Air Force overhaul facility after the altitude test and subsequently returned to inventory. The altitude tests demonstrated the flight-worthiness of both the hardware and the control modes as implemented in the software.

The other engine (P-676627) and associated electronic equipment was shipped to NASA/DFRC where it was installed in the F-111E test aircraft by a NASA crew. After a comprehensive ground checkout, a flight test series was conducted to evaluate the IPCS in a flight environment.

A full set of steady-state and transient engine and aircraft events was conducted at all the test conditions shown in Figure 1.1-4. Seventy-seven operating hours were accumulated on the engine during thirty five ground runs and fifteen flights.

Microfilm copies of the reduced data from the baseline and IPCS evaluation tests conducted at the NASA/LeRC altitude facility and at NASA/DFRC have been submitted to the Air Force Aero-Propulsion Laboratory (J. J. Batka), NASA/LeRC (J. R. Zeller), and NASA/DFRC (F. W. Burcham).

1.2 SIGNIFICANT RESULTS

The IPCS program successfully demonstrated operational advantages on the test airframe/engine installation, it demonstrated in a flight environment advanced technical features that had previously been studied only theoretically or in a laboratory environment, and it demonstrated a management methodology that can be applied to reduce cost and risk in the development of an integrated propulsion control system for a high performance aircraft of the future.

The IPCS operational advantages are listed in Table 1.2-1. These were achieved even though the propulsion system had not been designed to exploit the advantages of the advanced controller; no changes were made to the engine gas path or the inlet aerodynamic surfaces. It must be noted that the operational improvements are configuration-dependent; a different engine/airframe combination might exhibit other improvements.

The IPCS advanced technical features are listed in Table 1.2-2. The most significant advantage to be gained through application of these features is the ability to operate closer to the propulsion system limits for optimum steady-state thrust and fuel consumption, and to retreat from these limits momentarily to execute transients or to accommodate disturbances. Hence, the propulsion system and the control system must be designed concurrently in order to exploit fully the proffered advantages.

Table 1.2-1

DEMONSTRATED OPERATIONAL BENEFITS OF IPCS

Faster engine acceleration; both gas generator and afterburner.
Better thrust and SFC at some flight conditions.
Reduced thrust at flight idle
Reduce or eliminate ground trim requirements.
Extended service ceiling.
Automatic stall detection and stall recovery detection.

Table 1.2-2

IPCS ADVANCED TECHNICAL FEATURES

Integration of engine and inlet controls.
Full authority digital propulsion control.
Use of compressor discharge Mach number for surge protection.
Automatic detection and suppression of inlet buzz.
Control of compressor bleeds on sensed distortion
Fuel manifold prefill logic to smooth afterburner transients.

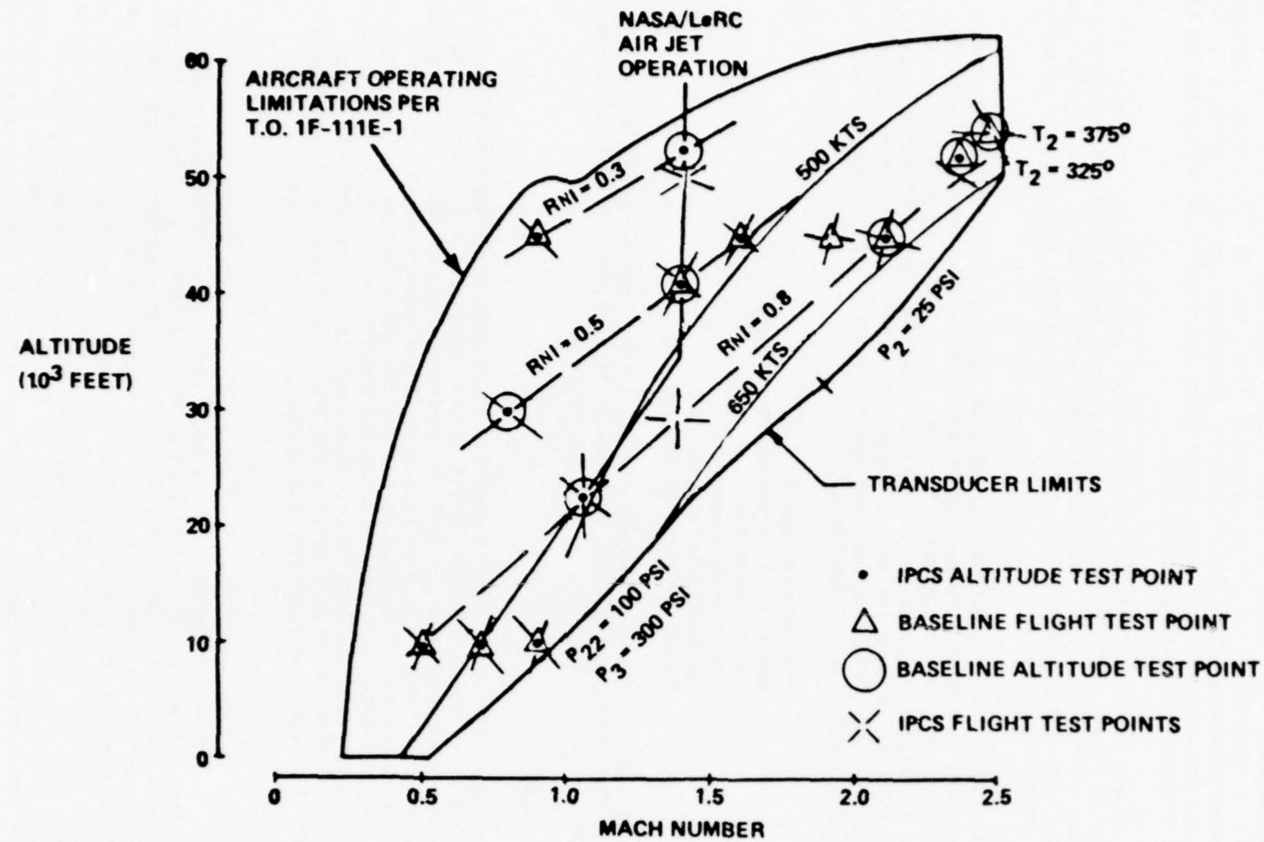


Figure 1.1-4 IPCS Program Test Points

2.0 IPCS METHODOLOGY

The essence of IPCS methodology resides in three simple concepts: (1) Early planning for integration, (2) Early involvement of all concerned parties, and (3) Freer interorganizational communication between personnel at all levels that is considered common in weapons system programs. Proper use and management of these three items has a profound effect on the cost, risk, and success of complex intercompany programs.

One contractor must have responsibility for making overall system studies and decisions. If the customer elects to retain this responsibility, he should be prepared for substantial involvement with the contractors in all aspects of their work; technical, contractual and financial. Configuration control of all components of the system, hardware and software, is another important responsibility.

The primary usefullness of the IPCS methodology document will occur in the early stages of the development program, when many important decisions must be made and the supporting technical staffs may not be fully organized. Our goal in preparing this document was to provide assistance in establishing the philosophy and direction that will minimize program risk and cost. To this end we have included discussions of both management methodology and engineering practice appropriate to the development of integrated propulsion controls as we would apply it. Specific areas treated are:

- Program management
- Development of system requirement
- Control mode design
- Software development
- Hardware development
- System integration and testing

We have attempted to identify the most important data, trades, and decisions that are required in each of these areas and provide guidance in finding the data and making the trades and decisions.

2.1 PROGRAM MANAGEMENT

Development of an integrated control system requires adaptation of management disciplines to the special situation in which equipment built by one contractor will operate under control of a computer system designed and built by another contractor to a set of requirements established by a contractor team. The main objective of the management effort is to ensure that available resources are applied to achieve the end objective most effectively. Existing corporate organizations generally provide the discipline and structure necessary for effective control, but modifications to accepted practice for maximum efficiency. Opportunities for redistribution of work outside the traditional boundaries of responsibility must be siezed when it is apparent that benefits to the program will result.

2.1.1 Planning

Careful planning is particularly important in the development of an integrated system which depends upon the interaction of several contractors and agencies. The concepts of IPCS methodology, early in planning for integration by all concerned parties and free communication must be applied to avoid delays and duplications of effort. A sequence of 64 events has been set down on the time line shown in Figure 2.1-1. Five major phases are identified that cover the period of time that starts with the identification of a system application and ends with the selection of contractors for development of the system prototype. Analysis is not shown as a phase since it is necessary to continue a comprehensive analysis effort for the duration of system development. The time line has been structured to fit an engine/supersonic-inlet integration program. If the program involves other integration aspects, e.g., a subsonic VSTOL program, it will be necessary to substitute other events.

This time line must obviously be converted to a more detailed multi-tiered schedule to permit precise tracking of milestones that measure progress and accomplishments of the program.

SYSTEM DEFINITION AND PRELIMINARY DESIGN

REQUIREMENTS

0

SYSTEM APPLICATION IDENTIFIED
PROPRIETARY AGREEMENTS - KEY PERSONNEL IDENTIFIED - COMMUNICATION FORMAT ESTAB.
PRELIMINARY SYSTEM DEFINITION

DEVELOPMENT PLAN - DIVISION OF RESPONSIBILITY - DOCUMENT TREE

ENGINE CONFIGURATION SELECTED

INLET CONFIGURATION SELECTED
BASELINE CONTROL MODES DEFINED

INLET AND ENGINE CHARACTERISTICS DEFINED

6

DIGITAL SIMULATION OPERATING

PRELIMINARY COMPONENT REQUIREMENTS DEFINED

FAILURE DETECTION & BACK-UP PHILOSOPHY
LINEARIZED MODEL AVAILABLE
PRELIMINARY COMPONENT SELECTION
UPDATE SYSTEM DEFINITION
ELECTRONIC INTERFACE DEFINITION
UPDATE DEVELOPMENT PLAN

SOFTWARE REQUIREMENTS DOCUMENTED
RELIABILITY REQUIREMENTS DEFINED
BASELINE CONTROLLER DEFINED

12

ENVIRONMENTAL REQUIREMENTS
ON/OFF ENGINE DECISION

UPDATE DIGITAL SIMULATION

1/12 SCALE INLET TEST COMPLETED

COST ESTIMATE COMPLETED

CONTRACTOR REVIEW

LINEARIZED MODEL UPDATED

SPECIMENS OF TRANSDUCERS AND OUTPUT DEVICES AVAIL.
ALL DOCUMENTS UPDATED

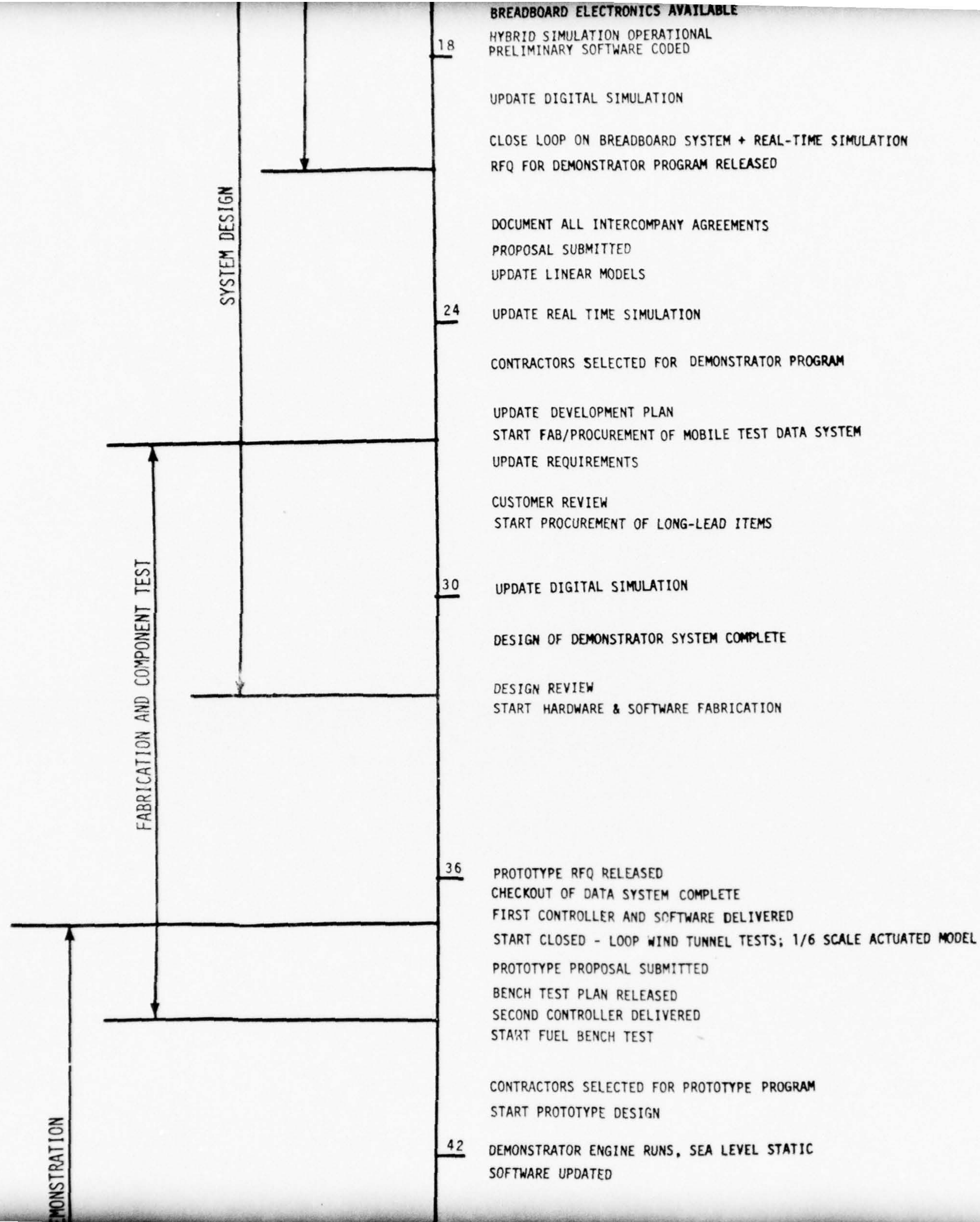
BREADBOARD ELECTRONICS AVAILABLE

18

HYBRID SIMULATION OPERATIONAL
PRELIMINARY SOFTWARE CODED

UPDATE DIGITAL SIMULATION

CLOSE LOOP ON BREADBOARD SYSTEM + REAL-TIME SIMULATION
RFQ FOR DEMONSTRATOR PROGRAM RELEASED


BREADBOARD ELECTRONICS AVAILABLE
18
HYBRID SIMULATION OPERATIONAL
PRELIMINARY SOFTWARE CODED
UPDATE DIGITAL SIMULATION
CLOSE LOOP ON BREADBOARD SYSTEM + REAL-TIME SIMULATION
RFQ FOR DEMONSTRATOR PROGRAM RELEASED
DOCUMENT ALL INTERCOMPANY AGREEMENTS
PROPOSAL SUBMITTED
UPDATE LINEAR MODELS
24
UPDATE REAL TIME SIMULATION
CONTRACTORS SELECTED FOR DEMONSTRATOR PROGRAM
UPDATE DEVELOPMENT PLAN
START FAB/PROCUREMENT OF MOBILE TEST DATA SYSTEM
UPDATE REQUIREMENTS
CUSTOMER REVIEW
START PROCUREMENT OF LONG-LEAD ITEMS
30
UPDATE DIGITAL SIMULATION
DESIGN OF DEMONSTRATOR SYSTEM COMPLETE
DESIGN REVIEW
START HARDWARE & SOFTWARE FABRICATION
36
PROTOTYPE RFQ RELEASED
CHECKOUT OF DATA SYSTEM COMPLETE
FIRST CONTROLLER AND SOFTWARE DELIVERED
START CLOSED - LOOP WIND TUNNEL TESTS; 1/6 SCALE ACTUATED MODEL
PROTOTYPE PROPOSAL SUBMITTED
BENCH TEST PLAN RELEASED
SECOND CONTROLLER DELIVERED
START FUEL BENCH TEST
CONTRACTORS SELECTED FOR PROTOTYPE PROGRAM
START PROTOTYPE DESIGN
42
DEMONSTRATOR ENGINE RUNS, SEA LEVEL STATIC
SOFTWARE UPDATED
SYSTEM DESIGN
FABRICATION AND COMPONENT TEST

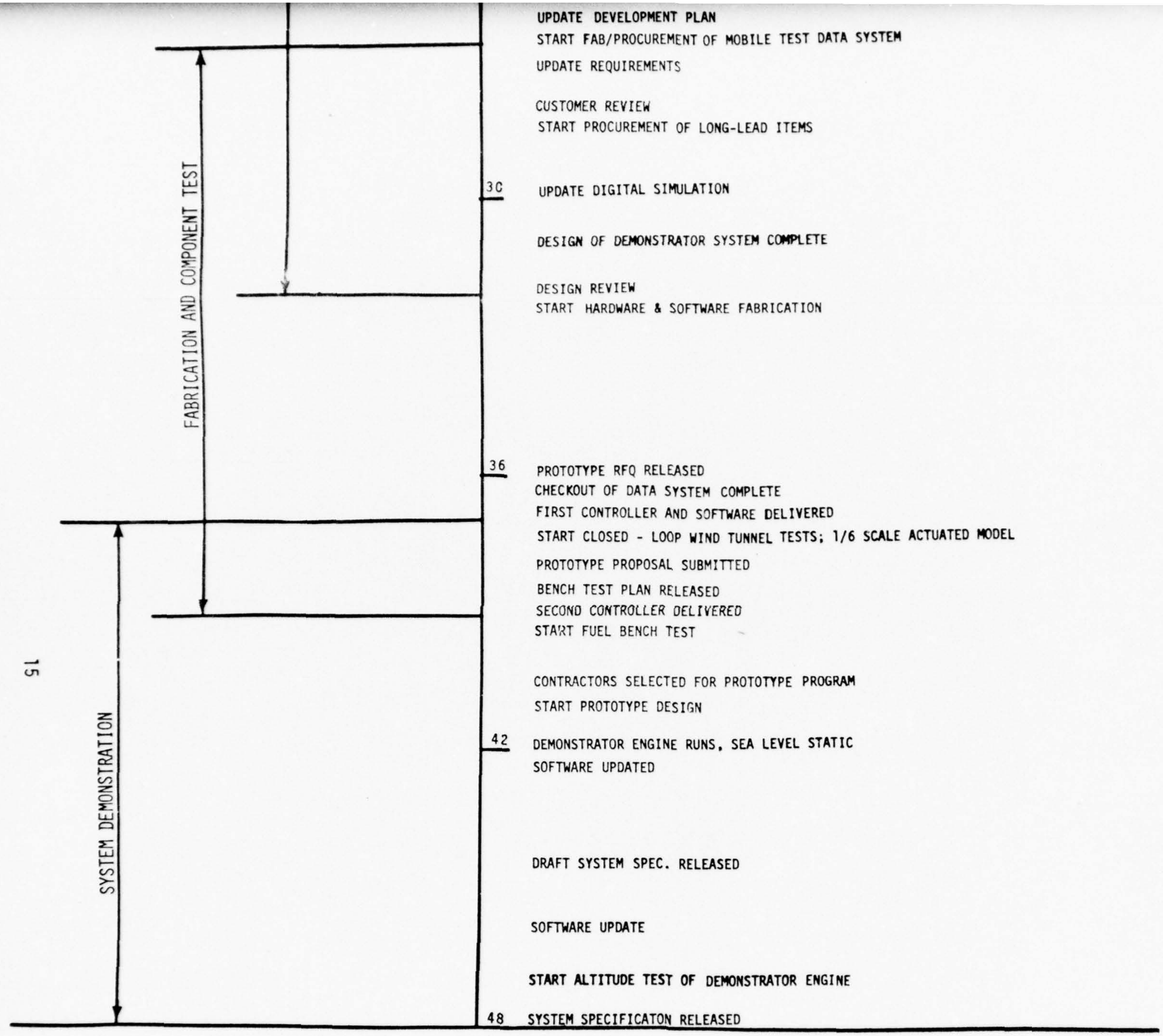


Figure 2.1-1 Demonstrator Program Milestone Time Line

3

The participation of each contractor and agency must reflect due concern for possession and scheduling of resources such as test facilities and computers. In many cases the facilities and capability are owned by the government. Availability and possible use of these facilities should be explored in depth. Technological capability must also be examined, such as that required for the design and manufacture of airframes, engines, electronics, and software.

2.1.2 Assignment of Responsibilities

Prospective participants in the system development should work out agreements covering the division of the task during the pre-contractual or competitive phase. The contractual relationships that are established will probably be determined by the nature of the anticipated procurement, as opposed to the relationship that may seem most attractive for the development of the integrated propulsion control. However, the working relationships should be established and documented consistent with the contractual constraints.

One contractor must have responsibility for making overall system studies and decisions. This contractor should have the responsibility for primary interface with the customer. If a single prime contract is anticipated, it would be logical for this responsibility to be assumed by the prime contractor. An integration contractor is another possibility. One of the associate contractors might have this responsibility in the case of a typical government weapon system procurement. If the customer elects to retain this responsibility, he should be prepared for substantial involvement with the contractors in all aspects of their work; technical, contractual, and financial. The importance of open communication in all links cannot be too strongly stressed. Configuration control of all components of the system, hardware and software, is another important responsibility.

The IPCS program was based on a prime/subcontract relationship in the belief that it provided the most efficient contracting mechanism. All the participants contributed to program direction, but control remained in the hands of the prime contractor with direct responsibility to the customer agency. This provided a very direct mechanism for rapid decision making. Justification for this approach lies in the fact that the 3-year program was complete precisely on the time schedule of the original contract.

The development of an integrated propulsion control system can be divided into four areas:

- Engine control modes
- Inlet/airframe control modes
- Control hardware
- Software

It would be natural, although not essential, that these packages be divided, intact, among the program participants. Cooperation between companies and inter-group flow of communication are essential. It is an absolute requirement that no unilateral decisions be made in one area that may impact another area.

The control hardware may be divided into sensors and actuators on the engine, sensors and actuators in the inlet and airframe, and the computer hardware. Engine and airframe manufacturers must retain ultimate responsibility for the structural integrity and operational characteristics (e.g., accuracy, band pass) of their respective sensors and actuators as well as the responsibility for plumbing, mounting brackets, etc. Responsibility for signal conditioning should be extended to include transducer excitation.

Integrated propulsion control development could also be divided by technology areas to take advantage of possible specialized skills of the participants. This situation has particular application where more than one of the contractors have similar capabilities, for example:

- Control mode design
- Electronic design and manufacturing
- Mechanical design and manufacturing
- Software engineering

The important objective of this approach is to maximize the integration and avoid duplication. This is a perfectly viable approach that has some advantages over the produce line approach if the organizational and contractual difficulties can be overcome. Cooperation among the contractors is essential. A good example is control mode design. In practice, the group charged with control mode design would probably include representatives of engine, airframe and control hardware manufacturers.

There are definite advantages to having computer hardware and software supplied by the same organization. The control algorithm is only one of several essential program modules. Some of these modules are hardware peculiar and can have a strong effect on the implementation of the control modes.

2.1.3 Communication

Communication among all parties down to the working engineer level is an essential function that requires support from management. All companies have developed disciplines and restrictions on the transmittal of information which are suited to their own situations, which are necessary for commercial and national security, public relations, and other responsibilities. These regulations must be adapted to the special needs of the integrated propulsion control system development.

Agreements should be developed to ensure proper protection of proprietary information. Intercompany agreements are essential to allow enough information to flow to do the job efficiently and conveniently. The point is to establish the channels for communication of all material, and to provide the necessary mechanism to prevent improper use of specific knowledge. A good example is a computer program which may be capable of specialized computations. Two-party agreements were executed between Boeing and P&WA , between Honeywell and P&WA, and between Boeing and General Dynamics in order to facilitate information transmittal in which each company agreed to use transmitted data only for the intended purpose to protect it, and not to make any unauthorized use of it. In each case, the two companies made reciprocal agreements and defined the formalities to be observed.

The contractors must be able to depend upon being able to work from a consistent definition of the system at all times. It is thus essential to maintain a formal system of documentation which the technical participants can use conveniently. Such a system is outlined in Figure 2.1-2. Some of these documents are normal requirements in the formal documentation of the contract, others are not. The document control mechanism must be flexible and easily used in order to ensure that updates are made when needed. The documentation system is the key to effective configuration control.

A configuration-controlled glossary of terms should also be provided in the System Definition document. Use of these terms should be required by all development areas to ensure compatibility.

Formal and informal transmittal of cost and schedule data are essential for program control. Routine monthly transmittal of information is not adequate for precise control, and informal supporting communication agreements may have to be set up to provide cost control. Visibility is necessary within a time frame to provide response which will control the costs. During periods of heavy expenditure rate, weekly updates of costs and schedules are probably necessary for effective intra-company, and inter-company control.

Use of direct verbal communication among team members is essential. Communication by telephone played a major role in the IPCS program. In order to permit a free exchange of technical information, each individual had to understand the overall program well enough to exercise sound judgment and make valid commitments. In addition, an efficient, internal telephone memorandum system was required to keep key personnel advised of the substance of the conversations. This technique proved effective for the small R&D effort, but the magnitude of a major development program could reduce this procedure to chaos unless discipline is practed. In that case, limiting the interchange to one individual in each key discipline might be equally effective and should not be a management burden. As an alternative, it might be feasible to assign to each individual a counterpart in the other company(s) that he may contact freely.

A small effort to use commonly available facilities such as speaker phones, three party conference calls and fascimile machines can considerably enhance the rate at which problems are resolved. Again it usually falls upon program managers to provide such facilities and encourage their use.

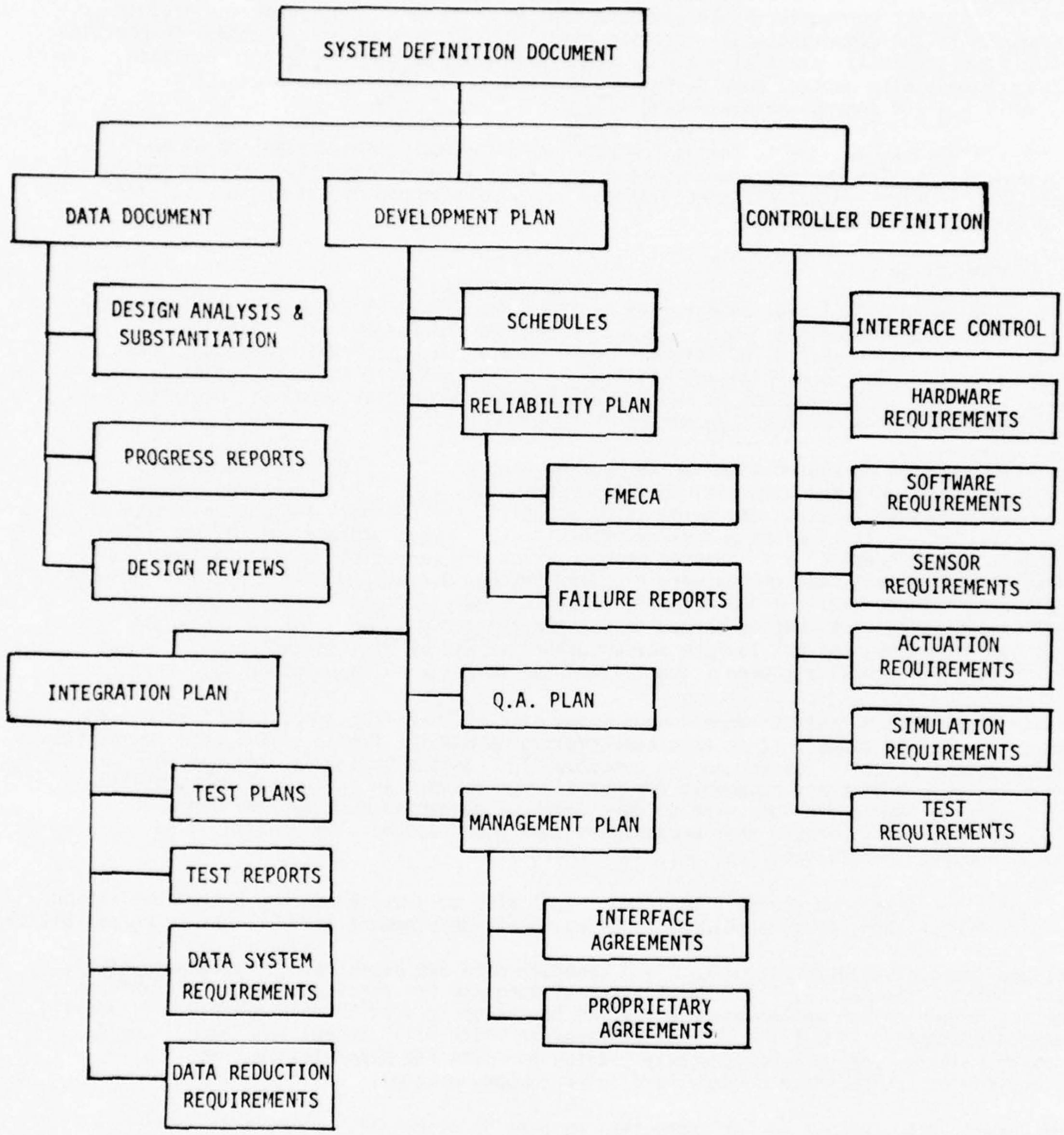


Figure 2.1-2 Document Tree

2.2 DEVELOPMENT OF REQUIREMENTS

The "development of requirements" is a term applied to those activities that lead to a detailed set of preliminary hardware component and subsystem requirements and software requirements. The major activities covered under this heading are the compilation of data, preliminary design of control modes, and trade studies. These activities should begin with the release of the Development Plan (see the time line in Figure 2.1-1) and should proceed concurrently with the preliminary design of the engine and airframe. Basically, they bridge the gap between the preliminary system definition and hardware and software design and procurement activities. The output of the activities discussed in this heading will be the following:

- A baseline controller configuration
- Definition of sensors and actuators required for control implemenation
- Electronic and physical interface definition
- Computer processor capability requirements
- Reliability and safety requirements
- Power requirements
- Environmental control and/or tolerance requirements

These activities will last approximately a year. Considerable interaction between control and performance groups should occur during this period for two reasons: 1) To ensure that propulsion system is controllable to the degree necessary to provide the performance levels being predicted by the performance group. 2) To ensure that performance/stability groups utilize the full range of flexibility offered by sophisticated controls. At the end of this time, a cost estimate will be possible and a contractor review should be conducted to evaluate the suitability of the baseline controller.

The development of component requirements is discussed in detail in Volume IV. Component requirements can be established only after the system has been defined and the basic control algorithm has been designed. This lends urgency to those activities because detailed hardware, software, and control mode design cannot proceed until component requirements are defined. In addition the maximum possible lead time should be provided for component development and/or procurement.

Reliability requirements are a subset of the component requirements but are listed separately because of the specialized skills needed to develop them.

The development of requirements is an iterative process that benefits from the free exchange of information. Initial estimates of requirements must be examined and updated as information becomes available.

2.3 CONTROL MODE DESIGN

Control mode design bridges the gap between the baseline design developed per paragraph 2.2 and the detailed definition of control modes required for physical implementation of the system. The following results are achieved in the process:

- Confirmation of the baseline control algorithm
- Development of logic networks
- Selection of gains, setpoints, and compensation
- Corroboration of component accuracy and frequency response requirements
- Development of failure detection and back-up modes

An analytical design team composed of working level personnel from the airframe, control, and engine companies should be established to perform the control mode design. Their fundamental design tool will be a non-linear digital dynamic simulation of the propulsion system and relevant portions of the airframe. A hybrid simulation used for specialized studies and software checkout and linear models used for loop design are derived from the digital simulation. The rapidly developing science of optimal controls should be explored for loop design.

2.4 SOFTWARE DEVELOPMENT

Conventional software development techniques were applied successfully during the IPCS program. It was concluded that verification testing should be done with the operational hardware and with the control loop closed by a real-time plant simulation. Field support during ground testing should include at least one software engineer to support test shift operations and one experienced individual whose primary responsibility is to design software modifications and maintain documentation.

2.5 HARDWARE DEVELOPMENT

Hardware development covers the specification, design, procurement or fabrication, and testing of components that meet the requirements discussed in paragraph 2.2. It is commonly found that the components needed to meet specific requirements are unavailable, impossible with existing technology, or more expensive than anticipated. The requirements must be reassessed and the options weighed. Hopefully the requirements can be relaxed. Otherwise the penalty must be assumed. If this is unfeasible it may be necessary to redesign the control mode to eliminate the offending requirement. A program to generate new component technology should be attempted only as a last resort.

2.6 SYSTEM INTEGRATION AND TEST

We strongly support the step-by-step approach to system integration and testing. Interface tests should be initiated by the controls manufacturer as soon as the hardware and software components become available. Final pre-delivery checkout of software should be performed on the actual control computer with its interface unit, using a real-time simulation to close the loop.

The IPCS fuel bench test procedure is sound and is adaptable to other programs. In addition, a closed-loop wind-tunnel test of a fully actuated inlet model is recommended, particularly if the inlet operates in a mixed-compression mode. Sea-level-static testing, followed by altitude testing of the demonstrator engine is recommended; initial tests would be run using a bell-mouth inlet. The introduction of a boiler-plate version of the flight inlet during the sea-level test program is desirable, particularly if the inlet is actuated during ground or low speed flight operation.

It is recommended that a data recording package be designed for use in ground and flight tests, together with a mobile data processing van that is moved from facility to facility during the entire test program. This approach will provide rapid data turnaround through the use of an on-site dedicated data processing facility and eliminate the requirement for interfacing with the facility data processing systems. Control mode development in the field would also be facilitated by a real-time simulation on site at the test facility to close the control loop for software checkout.

One of the conclusions drawn from this program is that the tests were too closely spaced on the schedule; there was not enough time between the tests to absorb the results.

3.0 IPCS PROGRAM TECHNICAL DESCRIPTION

Controls for early turbojet engines were direct and simple. Engine geometry was fixed and operating margins were generous, with engine fuel flow as the only independent variable. Satisfactory control was achieved through a simple speed governor. Acceleration and deceleration fuel flow limiting could be done with open-loop schedules. These requirements were readily satisfied by positioning a fuel valve through a system of cams and linkages that come to be known as the hydromechanical fuel control. Since the engine requirements were minimal, a suitable fuel control could be compact, lightweight, and highly reliable.

Twin-spool engines, turbofan engines, variable compressor geometry, and afterburners engendered a corresponding increase in the complexity of the control required for satisfactory operation. The progression to turbofan engines with fully modulated afterburners and exhaust nozzles placed severe demands upon hydromechanical control technology. The added complication of operation behind a supersonic inlet pushed the current technology of hydromechanical controls to an apparent limit, with costs increasing and little hope of maintaining a reputation for reliability. By contrast, both the cost and reliability of digital electronic controls have been improving rapidly and this improvement appears to be destined to continue. Furthermore, integration into a modern flight system demands communication, and direct communication with a hydromechanical unit is inherently difficult.

3.1 IPCS PROGRAM GOALS

The goals of the Air Force in sponsoring the IPCS program were two fold:

1. Improved aircraft systems performance through technological advances.
2. Reduce the cost and risk of future development programs through an expanded technical data base and demonstrated management methodology.

Specific goals established for the IPCS pursued the goals of the Air Force Exploratory Development Programs. The first of these was to develop, demonstrate, and evaluate in a flight environment, certain advanced technical features that have to date been explored only under very restricted conditions. These are listed in Table 1.2-2.

The second major goal was the development of an intercompany management approach applicable to the design and development of integrated systems. The IPCS management methodology addresses three areas of potential concern; assignment of responsibilities, communication and coordination between geographically remote organizations, and minimization of technical risk and cost through a timely test sequence. The salient features of the IPCS management approach are listed in Table 3.1-1.

Achievement of these program goals has identified potential development problem areas. It has generated a body of technical data upon which to base further development work and has provided a basis for estimating the time and cost of development of an operational IPCS.

Table 3.1-1

SALIENT FEATURES OF IPCS INTERCOMPANY MANAGEMENT APPROACH

Horizontal assignment of responsibility - each organization exercised its own area of expertise over the entire range of the program.

Direct communication at the working level was stressed.

Regular (monthly) coordination meetings were attended by representatives of the prime and major subcontractors.

Periodic working sessions were conducted with attendance by technical personnel of each of the three firms.

Progressive step-by-step hardware and software test sequence.

Final decisions were made by the prime contractor at government direction.

3.2 SYSTEM DESCRIPTION

The IPCS consisted of flight hardware, control modes, and ground support hardware. Two complete sets of hardware were fabricated or modified for the program. A brief description of each of these items, intended to help the reader to understand subsequent material, is given below. Additional information is given in the sections of this report that treat the design, fabrication, and testing of the individual component and subsystems.

3.2.1 IPCS Flight Hardware

A diagram of the IPCS is shown in Figure 3.2-1. The TF30-P-9 engine was modified by P&WA to the extent required to interface with the Digital Propulsion Control Unit (DPCU). Pressure transducers. temperature sensors, and tachometers defined the engine state to the DPCU, which evaluated this information and generated commands that were transmitted to the modified fuel and nozzle controls. An electrical torque motor servo first stage was installed on the main fuel control. A selector solenoid was added so that the fuel metering valve could be driven either by the electrical first stage or by the hydromechanical bill-of-materials fuel controller, which was retained. Metering valves for each of the five afterburner zones were driven by stepper motors acting through hydraulic boosters. The exhaust nozzle actuator pilot valve was also driven by a hydraulically boosted stepper motor. Position feedback sensors were provided for all fuel metering valves, the exhaust nozzle pilot valve, and for the nozzle itself. Solenoids were added to operate the shut-off valves for the five afterburner zones and the nozzle. These solenoids, as well as the main fuel control sector solenoid, were selected so that interruption of electrical excitation would drive the engine to a safe operating condition; afterburner off, nozzle closed and gas generator under hydromechanical control. The 7th stage compressor bleeds were made to be operable under either DPCU or bill-of-materials control. The DPCU could open the 12th stage bleeds but could not override the bill-of-materials (PRBC) control to close them.

No changes were made to the engine cycle or to the gas path except as required for the installation of sensors. Only the actuation system was modified in the fuel and exhaust nozzle controls; all the service-proven fuel plumbing was retained.

The inlet actuation system was also modified as necessary to interface with the DPCU. The bill-of-materials hydromechanical inlet control was removed and replaced by a servo module that responded to computer commands. This module also had a solenoid-operated selector valve that caused the inlet surfaces to move to the low-speed configuration when excitation was interrupted. Pressure transducers were provided to sense inlet control signals and position feedback sensors were provided to close the position loops. The inlet aerodynamic configuration was not modified in any way.

The DPCU consisted of four major components; the digital computer unit (DCU) and interface unit (IFU), a power supply unit (PSU) and a computer monitor unit (CMU). The DCU was a Honeywell HDC-601 digital computer with a repertory of 84 instructions. (It has a core memory with 16,384 words divided into 32 sectors of 512 words each. Word length was 16 bits and memory cycle time was 1.2 microseconds.

The IFU was designed and built especially for the IPCS program. The input and output capability of the unit is given in Table 3.2-1. The IFU incorporated three custom input channels based on the supersonic transport buzz detector circuit, one each to detect inlet buzz, inlet air turbulence associated with distortion and afterburner rumble.

The CMU was mounted in the cockpit and was the interface between the flight crew and the DPCU. All control switches and displays were mounted on the CMU panel, which is diagrammed in Figure 3.2-2.

It was originally intended that the power supply be incorporated in the IFU. This plan was modified when it was determined that the flight-qualified stepper motors available for the fuel system modification required 32 vdc rather than the 28 vdc ships' power that has come to be accepted as the industry standard. The requirement for 32 vdc for the stepper motors imposed the requirement for a separate power supply unit (PSU) after the electronic hardware was well into the development cycle.

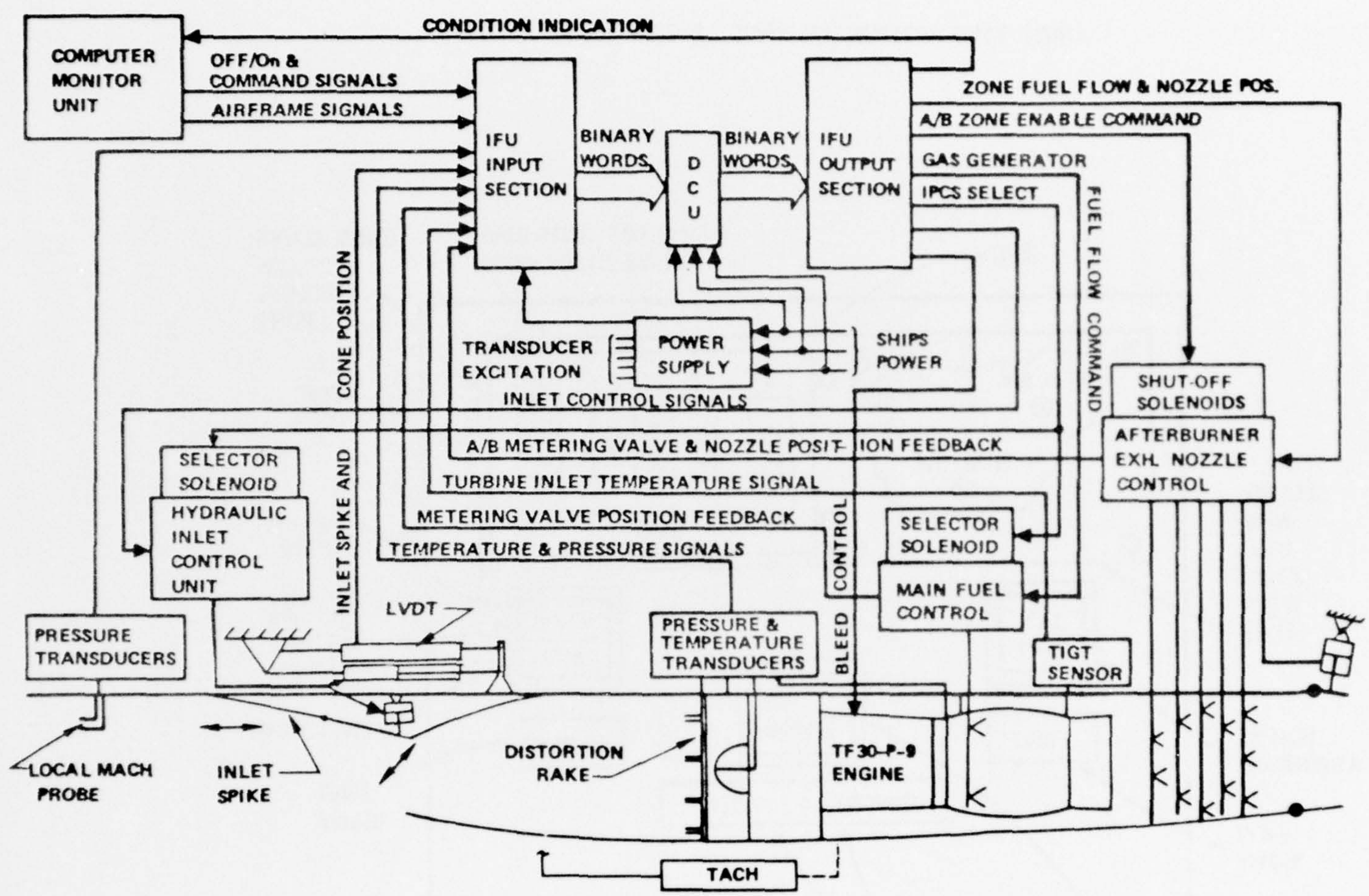


Figure 3.2-1 Integrated System Diagram

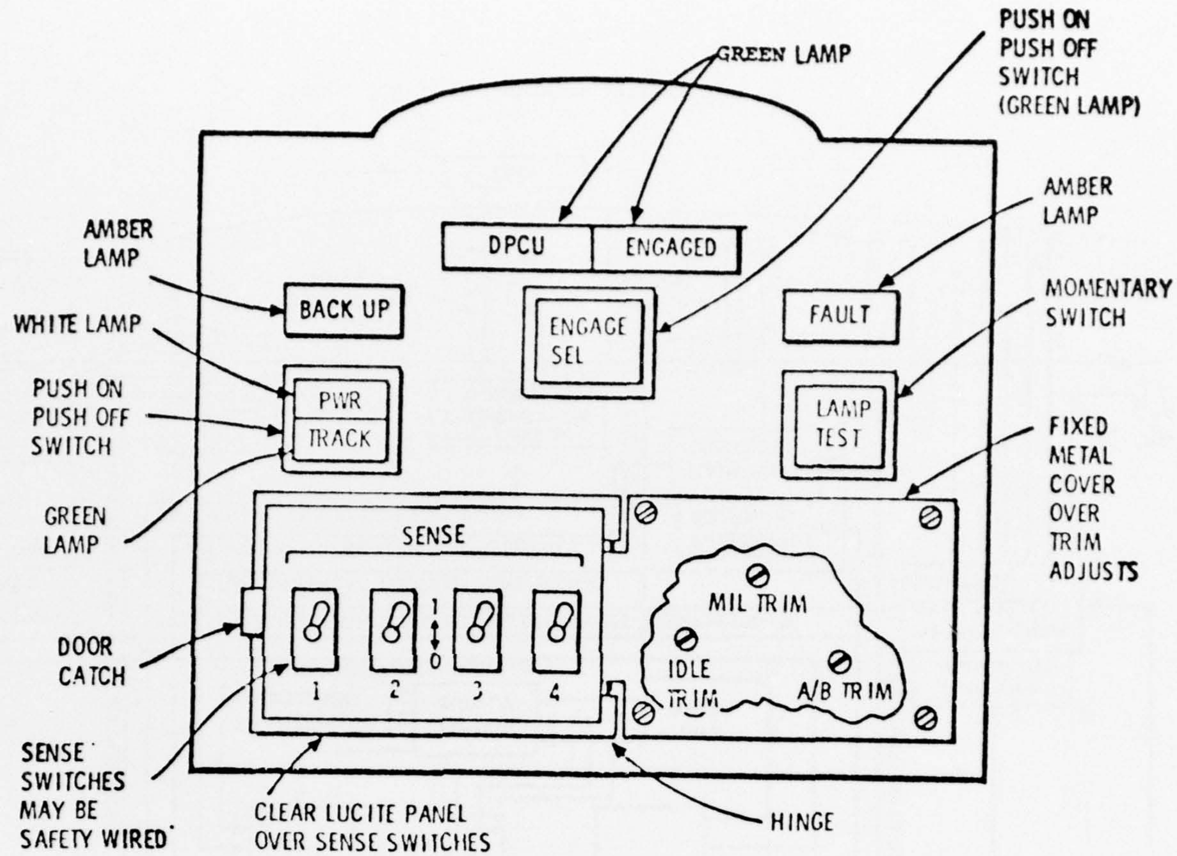


Figure 3.2-2 Computer Monitor Unit (CMU)

The layout of the IPCS on the aircraft is shown in Figure 3.2-3. The figure also shows a shock position probe and an instrumentation package. The shock probe was flown for evaluation only during preliminary (baseline) tests; the results of these tests are discussed in Volume II. The instrumentation package supplied by NASA/DFRC is discussed in detail in Volume III of this report.

The IPCS was installed in the aircraft by NASA personnel. Wire bundles and tubing runs were fabricated by NASA to Boeing drawings. Engineering support was provided on-site by the contractor team during the installation.

Table 3.2-1

Input/Output Capability of the Interface Unit

INPUT:		
	Low-level analog (30 mv)	32 channels
	High-level analog (5.12 volt)	32 channels
	16-bit discrete word	1
	Resolver signal processing	8 channels*
	Frequency output pressure transducer	8 channels*
	Tachometer	2 channels*
	TIGT sensor	1 channel*
	LVDT (converted to analog)	5 channels
OUTPUT:		
	Analog ($\pm$10.24 volts dc)	16 channels
	Torque motor drivers (amplify D/A output)	3 channels
	Stepper motor drives (from DIO)	6 channels
	16-bit discrete words	3 channels
	PCM interface	59 words

*Direct conversion from frequency signal to digital word.

3.2.2 Control Modes

The IPCS engine could be operated in any one of three control modes; hydromechanical, under computer control using a digital representation of the bill-of-materials controller (BOMDIG), or under computer control using software that implemented the advanced technical features listed in Table 1.2-2 (IPCS).

The hydromechanical mode employed the bill-of-materials unit that was retained for the gas generator only. This control mode was used both for a back-up in case of computer failure and as a baseline to evaluate the performance of the digital system.

The BOMDIG program incorporated the same schedules, setpoints, and logic that the hydromechanical controller was designed to implement. No attempt was made to simulate the dynamics of the hardware components or the hysteresis, deadbands, stiction or other idiosyncrasies of mechanical devices. The IPCS software program implemented the control laws that are discussed in Section 2.3 of Volume II.

A continuing effort was made during software development to achieve maximum commonality between the two programs. Commonality was pursued in the area of DCU self test, transducer signal conditioning, actuator command processing, etc.

3.2.3 Ground Support Hardware

Ground support equipment (GSE) was provided to service and test the flight hardware and to communicate with the DCU. The GSE consisted of a Test Set Unit (TSU) and an ASR-35 teletypewriter (TTY), associated software, and interconnections. The TSU was a rack-mounted system consisting of a computer control unit (CCU), a high speed paper tape reader, a paper tape punch, a duplicate of the CMU that was mounted in the cockpit, a DVM, displays, and specialized simulation and test circuitry.

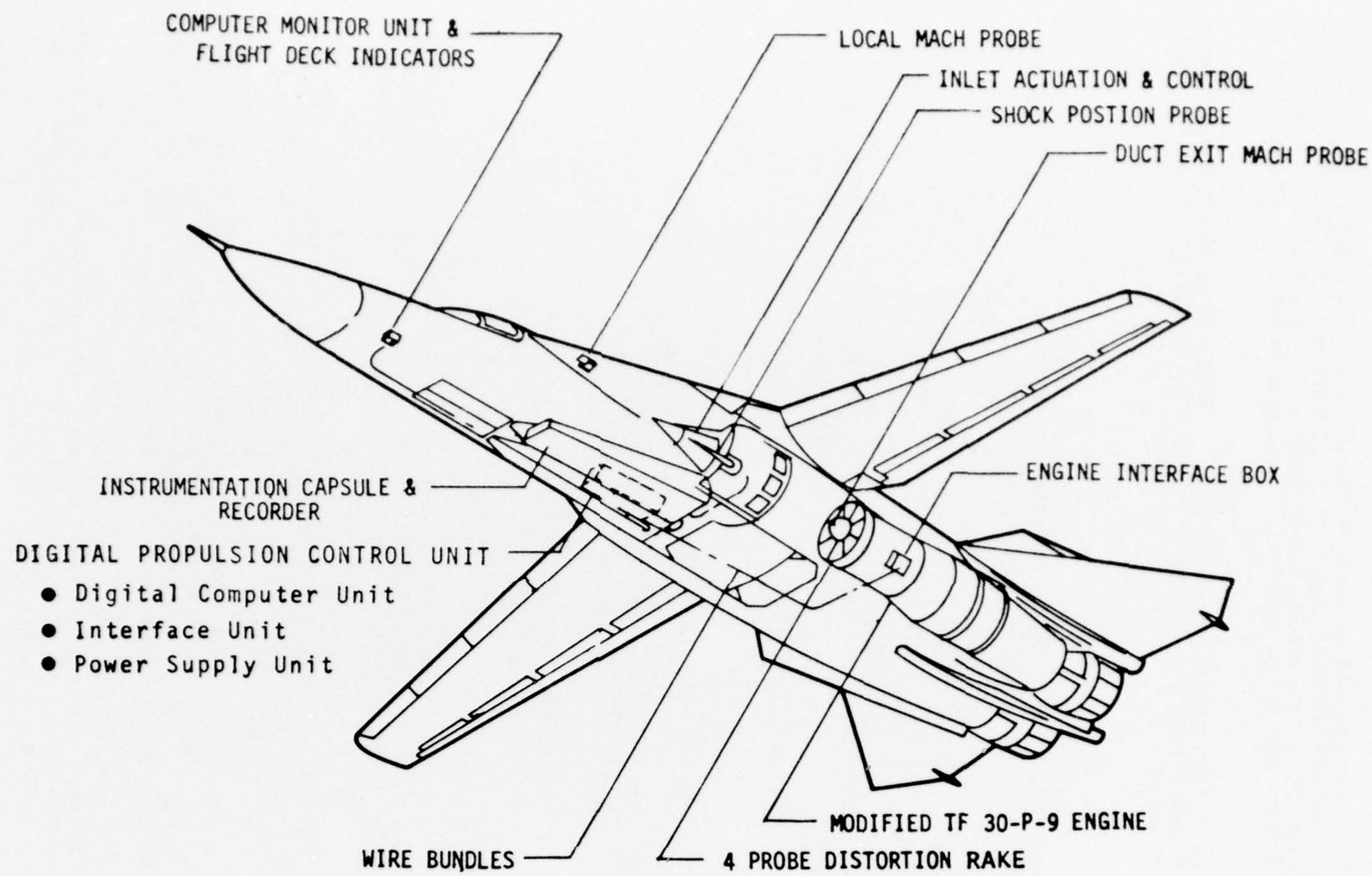


Figure 3.2-3 Layout of the IPCS on the Test Aircraft

The TSU could be used to check out the IFU and DCU when these components were disconnected from the engine installation. Steady-state and sinusoidal perturbations of sensor outputs for selected engine operating conditions could be presented to the IFU input. The IFU outputs could be monitored at test jacks on the TSU front panel.

The TSU also incorporated a recorder monitor panel that simulated the NASA PCM data system. This feature made it possible to display on-line and in real time, any one of fifty-nine preselected words directly from the computer memory. Any variable that was assigned a permanent location in memory could be selected for display. This capability was extremely useful during ground-test operations.

3.3 TEST PROGRAM

A sequence of hardware tests was conducted to evaluate the IPCS. This series progressed from baseline evaluation of the bill-of-materials system in a low risk, step-by-step manner through flight evaluation of the IPCS. The test flow is diagrammed in Figure 3.3-1. This test program provided high confidence of success at each phase due to the gradually increasing complexity of the tests.

Hardware components were subjected to flight assurance tests under the appropriate government specifications. The software was loaded into the control computer at Honeywell and checked out using a real-time engine simulation to close the loop. The Digital Propulsion Control Unit (DPCU) was integrated with the modified engine fuel controls for the first time at a closed-loop bench test at the P&WA facility. Again a real-time engine simulation was used to close the loop.

A series of three ground tests with the engine run under DPCU control followed; a sea-level static test at P&WA, an altitude test at NASA/LeRC, and a ground test, with the engine installed in the aircraft at NASA/DFRC. These tests provided further flight assurance and verified hardware and software compatibility. They provided the means for refining the control modes and software, bringing them to maturity.

The system-level test points are shown in Figure 1.1-4, which also shows the operating envelope of the TF30-P-9 engines as modified for the IPCS program. The philosophy was to operate along lines of constant Reynolds index and to limit the maximum engine operating pressure, thereby reducing structural loads on engine components and restricting the range of operation of the pressure sensors.

3.3.1 Baseline Tests

Baseline engine and flight tests were designed to document the performance of the F-111E/ TF30-P-9 system prior to the IPCS modifications. During the baseline engine test, the two engines to be modified for IPCS were tested over a range of flight conditions to establish steady-state and transient performance and distortion tolerance. Data from the test have been analyzed and used to update the dynamic simulation. The baseline flight test provided similar data for the airplane and inlet.

The Distortion Computer shown in Figure 3.3-2 with its test set was a useful asset to the baseline tests. The computer is installed in the instrumentation package in the airplane and computes KD2 in-flight. The distortion level is thus known to the pilots via a cockpit guage and to the engineers via telemetered data, permitting exploration of the operating limits of the propulsion system.

The baseline test program is discussed in Section 5.0 of Volume II.

3.3.2 Subsystem Tests

Individual component performance and physical integrity were demonstrated, where necessary, through component and subsystem test. Individual components were subject to environmental tests, temperature cycling and vibration in particular, as required by the NASA specification 21-2. The DPCU hardware and software were thoroughly checked out prior to shipment from the Honeywell facility as indicated earlier.

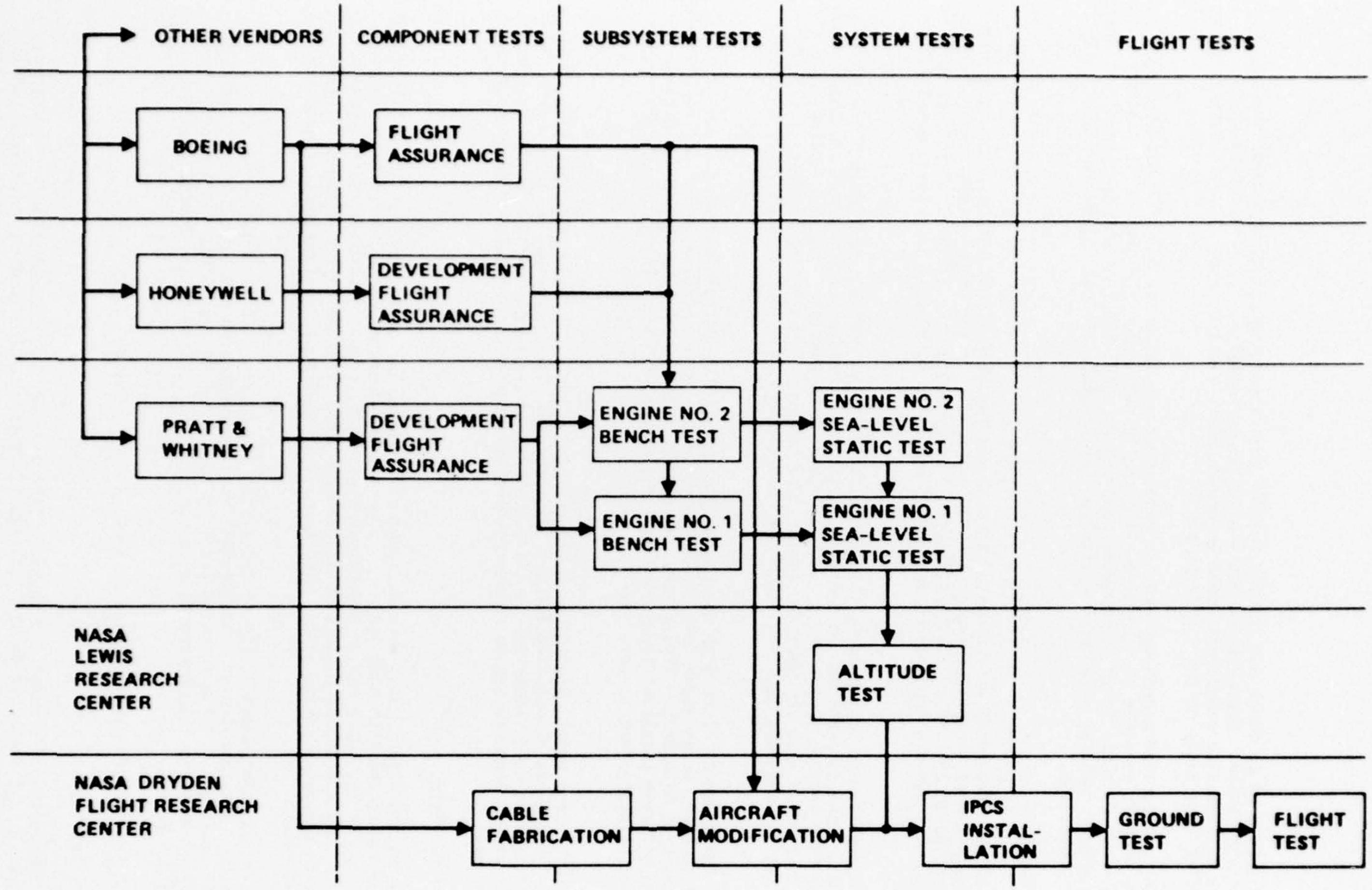


Figure 3.3-1 Test Flow

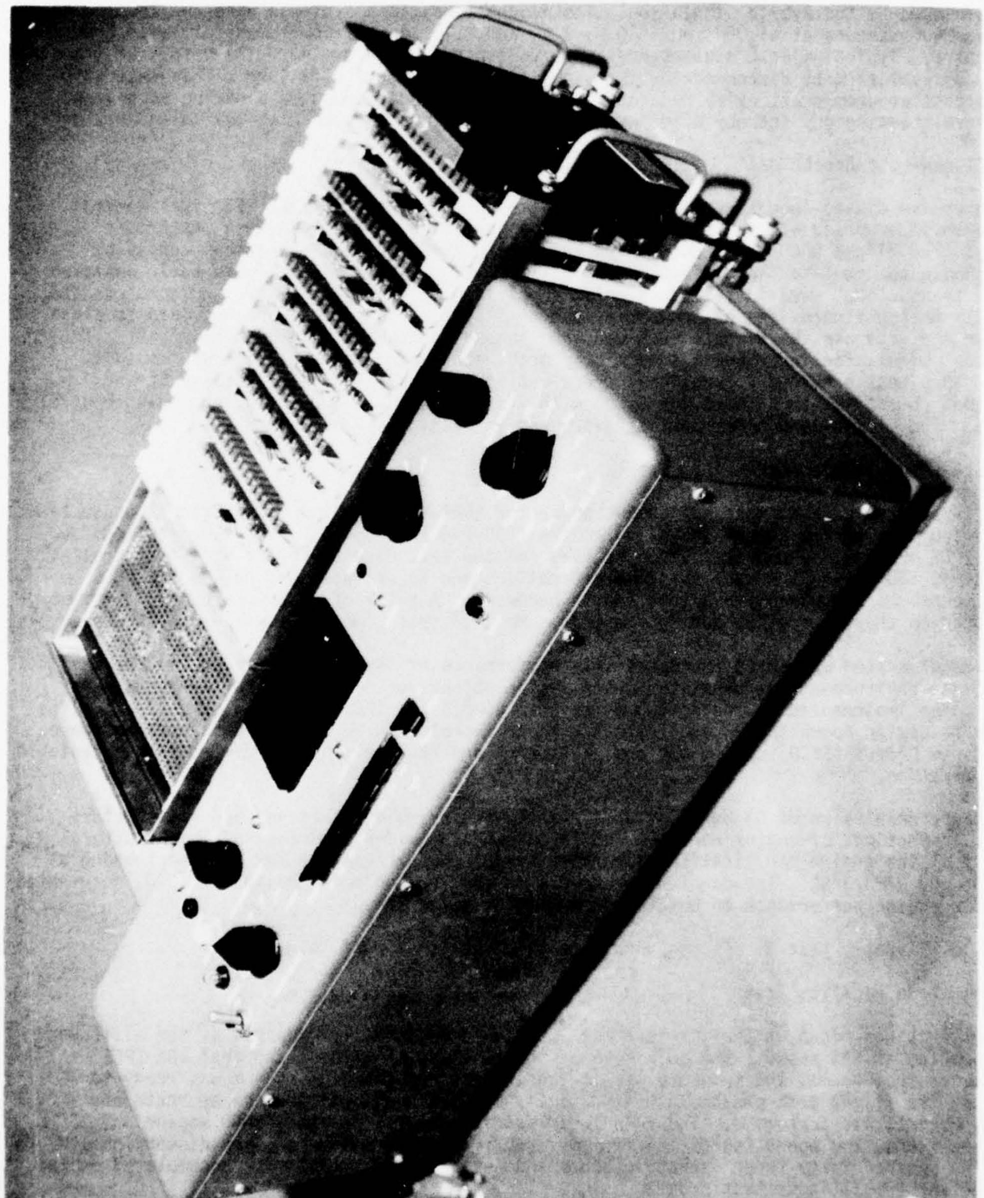


Figure 3.3-2 Distortion Computer and Test Set Unit

The control software was loaded into the HDC-601 flight computer and tested in real time with the loop closed by the hybrid simulation. The flight conditions explored were sea level static and three Mach numbers at 45,000 feet: 0.9, 1.6, and 2.1. A full complement of power transients was executed. Typical flight disturbances were presented to the system. The effect of transducer failure was evaluated by disconnecting the signal lines to simulate failure. This extensive in-house test program drastically reduced the number of "bugs" encountered during subsequent system-level testing and thereby effected significant savings in both cost and calendar time.

3.3.3 Closed-Loop Bench Test

A comprehensive closed-loop bench test followed the component tests. The TF30 fuel control, modified to incorporate electrical interfaces, was installed in the P&WA fuel bench test facility. The flight DPCU was connected to the fuel control through electrical cables of length chosen to simulate the aircraft installation. The inlet acuators, with their position feedback transducers, were installed in a jig supplied with hydraulic power, and connected to the DPCU. Analog simulations of the engine and the inlet aerodynamics were provided to close the loops and generate the signals that would be sensed by transducers in the aircraft. In some cases, simulation interface adapters were provided to simulate the transducer output format. This test provided a functional check out of the modified fuel control unit and established compatibility between the DPCU, with its software and the engine and inlet control hardware. The closed-loop bench test is discussed in Section 6.0 of Volume II.

3.3.4 Sea-Level Static Test

The sea level static (SLS) test was conducted at the P&WA facility in East Hartford. Connecticut. The modified fuel controls were installed on the TF30-P-9 engines that also had been modified for the IPCS program. The principal objectives of the test were to verify the structural integrity of the engine and fuel system modifications and to evaluate and refine the IPCS control modes and software with actual engine hardware. A total of 98 hours running time was accumulated on the two engines during the test. Most of this time was spent under DPCU control.

Evaluation of system operation indicated that performance of the IPCS components in the sea level engine environment was consistent with design objectives. The DPCU software and the control modes implemented in the software for both BOMDIG and IPCS exhibited several anomalies relative to design operational requirements. These anomalies were corrected through Software Field Change Orders (SFCO) during the engine testing and then retested to demonstrate acceptable engine operation.

Satisfactory completion of 98 hours of steady state and transient testing, and satisfactory periodic inspections of engine hardware and IPCS probes provided assurance of the structural integrity of the engine modifications, and they were judged acceptable for further testing at NASA/LeRC and NASA/DFRC. The concluding acceptance test run on both engines per T.O. documented acceptable engine performance on both engines with no deviations.

The sea-level-static test is discussed in detail in Section 7.0 of Volume II.

3.3.5 Altitude Facility Test

The investigations begun at the SLS test were continued and greatly expanded at the altitude test conducted at NASA/LeRC. The objective of the test was to demonstrate that the IPCS hardware, control modes, and software were flight worthy and that the system was ready to proceed to the flight test phase of the program. A comprehensive set of steady-state and transient events was performed. These included accels, decels, bodies,, DPCU engage and disengage events, and operation of the facility "puff-jets" to simulate inlet distortion and buzz. Two hundred forty three operating hours and seventy nine stalls were accumulated on the engine during the altitude test program.

The altitude test is discussed in detail in Section 8.0 of Volume II.

3.3.6 Flight Evaluation of the IPCS

The final checkout of the IPCS system was the first evaluation test series conducted at NASA/DFRC. The DPCU and a TF30-P-9 engine modified for the IPCS program were installed in a F-111E aircraft. The objectives of the tests were to demonstrate hardware capability and to evaluate operation of IPCS control modes and hardware in an actual F-111E aircraft flight environment. The flight tests also provided the first opportunity for evaluation of the inlet buzz detector and closed-loop control on sensed inlet distortion in a realistic environment.

A full set of steady-state and transient engine events (accels, decels, bodies, DPCU engage and disengage events, etc) were conducted at all test conditions shown in Figure 1.1-4. Operation of the IPCS system was also demonstrated for steady-state and transient aircraft events (accels, decels, angle-of-attack pull ups, etc.). Seventy-seven operating hours were accumulated on the engine during thirty five ground runs and fifteen flights.

The flight evaluation of the IPCS is discussed in detail in Volume III "Flight Test Report."

4.0 SUMMARY OF FLIGHT TEST RESULTS

The flight test was the last in the series of tests to evaluate integrated digital control of the F-111E propulsion system. Its purpose was to demonstrate the feasibility of digital propulsion control in a flight environment. The flight test program consisted of 15 flights in which both BOMDIG and IPCS were tested to the Mach number and altitude limits of the airplane. Comparisons were made between the hydromechanical control (HMC), BOMDIG and IPCS at flight conditions throughout the flight envelope (Figure 1.1-4).

A series of engine ground runs were conducted on each control mode prior to flight testing. These tests served to document the system static performance, identify and correct any problems, check out the data system, and demonstrate the flight worthiness of the DPCU installed in the airplane. As a result of the previous testing, most of the preflight testing was routine. The problems were largely confined to data system interfaces, control room displays, etc. The flight test program was designed to progress from the relatively easy tasks to the more difficult. The initial testing was performed on BOMDIG. The first few IPCS flights documented the IPCS performance with a basic control design without many of the special control loops. In this way system flight experience was gained prior to beginning the more difficult tests.

The testing demonstrated that digital propulsion control system is effective. The following operational advantages were demonstrated in the flight test program.

- Faster engine acceleration for both gas generator and afterburner operation
- Better thrust and SFC at certain flight conditions
- Reduced flight idle thrust
- Accurate, stable trim set points which compensate for engine deterioration
- Extended service ceiling
- Automatic stall detection and stall recovery detection providing "hands off" return to the original power setting.

The initial flight testing established that the BOMDIG control of the engine was comparable to hydromechanical control. The early IPCS flights showed that the basic IPCS without the special loops worked properly. This testing also demonstrated the advantages of the IPCS afterburner control. The manifold prefill logic anticipates the need to open the fuel shutoff valves eliminating the dead time associated with manifold filling. This resulted in an 11% to 44% reduction in acceleration time relative to HMC for the Mil to Max transient. This was accomplished without any degradation in fan stall margin. During decelerations IPCS had more fan stall margin due to the deliberate lagging of nozzle area relative to fuel flow.

During the later flights (21-28) the special IPCS loops were evaluated. In addition a number of changes were made to the high compressor exit Mach number, MN3, control to reduce gas generator acceleration time. Four variations of MN3 control were tested: the basic integral control, the integral control with higher gain (ground test only), a non-linear control operating at the major cycle rate (33 Hz), and the non-linear control operating at the minor cycle rate (200 Hz). The results of these tests indicates that the MN3 control is a viable alternative to Wf/Pb control as discussed in Volume III, although it does not solve all the gas generator control problems. Operation with MN3 control resulted in faster engine acceleration than HMC.

A measured distortion signal was used to control the compressor bleeds, opening the bleeds only when the distortion approached the engine tolerance to distortion. This permitted the 7th stage bleed to remain closed over a significantly larger portion of the flight placard than for the bill of materials bleed control. Closing the 7th stage bleed increases thrust and reduced SFC. If operated on both engines this feature could result in a 35% increase in Specific Excess Power which is equivalent to approximately 3000 feet increase in service ceiling.

Compressor stall was detected by measuring the rate of decay of burner pressure and comparing it to a reference schedule. Once stall was detected the engine PLA was set to idle and the bleeds opened. This feature was successfully demonstrated at a wide range of flight conditions. It was able to detect all but very low power stalls and it did not give spurious stall indication during throttle transients.

During the later portion of the flight test a stall recovery detection scheme was added. Recovery was detected by comparing burner pressure level to a reference curve. Stalls that recover quickly (pop-stalls) were accounted for by checking the recovery curve for 1 second after stall detection and not taking action if recovery was accomplished within one second. If not, the bleeds were opened and the engine PLA set to idle. Once stall recovery was detected the engine is returned to the power setting corresponding to the cockpit throttle position without any pilot action. Stall detection and recovery was demonstrated on flight 25 at Mach 1.4 and 41,000 feet.

A portion of the testing was devoted to evaluation of potential noise reduction by controlling the exhaust velocity profile. The intent of this testing was to obtain static and flight data to evaluate the potential noise benefits of duct burning engine. In a duct burning engine the velocity is highest at the outside of the jet and low in the core where there is no after burning. Afterburner fuel distribution was modified to produce this type of profile by operating at maximum zone 4 and reducing the core fuel flow. This was compared to maximum zone 5 with all fuel flow reduced to produce the same thrust. Noise, thrust and velocity profile measurements were made on the ground and noise measurements were made on a series of flight test points. Analysis of these data is continuing separately from the IPCS program. Preliminary results indicate that the desired profiles were approximated resulting in some noise reduction.

Throughout the test the advantages of the flexibility of digital control were apparent in the ability to identify and correct controller problems. The opportunity to adjust gains and schedules on a run by run basis greatly facilitated development of the control. The testing of the high compressor exit Mach control in which the control mode was changed from integral to non-linear is an example of the degree of flexibility of the control. Noise testing is another example . The decision to evaluate noise was not made until the middle of January. No provisions for or consideration of noise testing were included in the original control design, but it was possible, in a relatively short time, to develop a configuration for the noise testing.

A problem that became apparent during the course of the test was that the ability to refine and improve the controller had far outstripped the ability to process the data needed to identify the potential improvements. As a result changes to the control which might have greatly enhanced the test were not recognized until too late for orderly incorporation. Therefore, it is strongly recommended that a data processing system be used in future tests that provides turnaround of printed and plotted data in approximately 24 hours.

Control mode development would also be facilitated by a real-time simulation on-site to close the control loop for software checkout.

5.0 RECOMMENDATIONS

Several areas have been identified where further exploratory work could facilitate the development of a future integrated propulsion control system. These are discussed below. Some level of effort is currently being carried forward in some of these areas; this current work should be evaluated for applicability to propulsion control and extended as necessary.

Electronics configuration: Recommendations for trade studies are given in Section 3.0 and 6.0 of Volume IV, Methodology. Perhaps the most important of these relate to power source (dedicated alternator/MIL-STD-704/essential bus) trades.

Reliability: Most misgivings about the use of electronic control stem from concern about reliability. Development of reliable components is being pursued in many areas. In addition, a realistic set of reliability, failure detection, and failure response requirements should be established for propulsion control.

On-Engine or Off-Engine Controller: The relative advantages of the two possible controller locations should be assessed quantitatively.

Back-up Controller: The relative merits of hydromechanical, limited-capability electronics, or full-capability dual (multi-) channel electronics should be established.

Simulation: Improved methods for real-time simulation of propulsion systems for control design and on-site test support should be developed.

Filtering: Techniques for filtering signals from digital-output (frequency-output) transducers without penalizing the digital processor are needed.

Digital compiler: An efficient compiler for a high-level programming language might reduce the cost of software significantly.

Ground check-out: Requirements and techniques for ground check-out of an operational IPCS must be developed.

Flight/Propulsion control integration: Only the most cursory exploration has been done in this area. Basic concepts remain to be developed and evaluated. Applicability of existing analytical techniques must be demonstrated and/or new techniques developed. Simulation and test requirements and techniques must be established.

Contractual instruments: The mechanism for specifying applicable aspects of IPCS methodology must be evolved.

Data Systems: Turn-around of test data much more rapid than that achieved on the IPCS program is considered essential for a cost-effective test program.

Aircraft Data Bus: Automated data transfer between on-board computers is an attractive capability of digital systems. A data bus to provide the interface must be defined; trades such as word format, electronic or fiber optics links, etc., must be explored.

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